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Yellow is green: An opportunity for energy savings through colour in architectural spaces

J. López-Besora*, A. Isalgué[1], H. Coch[1], I. Crespo[1], C. Alonso[1]

Architecture & Energy, School of Architecture of Barcelona, UPC, Av. Diagonal, 649, 7th floor, 08028 Barcelona, Spain

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ABSTRACT

Today, the building sector is one of the greatest energy consumers of the world. Therefore, it is important that designers think about strategies to save energy at the different stages of the building process, including during its life. Considering that a great deal of energy will be spent in artificial lighting, an improvement in the performance in front of light of the architecture itself could lead to a better vision of the spaces, which depends on the quantity and quality of light available and on the architectural characteristics as well. One of the most influential aspects is the colour of the space. Here, a case study is presented in which three coloured spaces were assessed by observers under different lighting conditions. Luminance and illuminance measurements were taken to compare these values with the votes given. The results query the correlation between measured values and luminosity of three-dimensional spaces. As a consequence, the choice of a particular colour may increase the sensation of light in a space and, therefore, a reduction of energy use in artificial lighting is possible. In addition, architectural design can take advantage of colour to improve the visual quality of indoor spaces.

1. Introduction

Today, a large part of the energy consumed in the world is related to the building activity. In most countries, it is the main source of the greenhouse emissions to the atmosphere. It is associated to the large amount of energy spent during the periods of construction and life of the building. During its life, a high percentage of energy will be consumed for lighting, heating, cooling, ventilation, appliances and others. In that sense, energy savings can be achieved through a range of measures including smart design, improved insulation, low-energy appliances, high efficiency ventilation and heating/cooling systems, and conservation behaviour of building users [1]. According to that, "green building" designers may take several strategies to make feasible these energy savings.

Here, we focus on lighting and architecture, and its potential to reduce energy consumption during the life of the building. As it is widely known that the integration of daylighting in architecture is the best option to optimize the use of artificial lighting, this integration must be accurate in order to obtain the quantity and quality of light required and to avoid an undesired excess of light. According to that, many aspects like windows, glazing, interior finishes, skylight, light shelves, light wells and light pipes, as well as the harmonization of the daylighting and lighting interaction must be taken into account so as to get an optimal result [2]. Although the attention is usually focused on the characteristics of windows and glazing, in order to predict the amount of light available in the interior, other aspects like a smart design of the interior finishes are also important. In that sense, one important characteristic is the colour used on surfaces shaping a space.

As a physical phenomenon, colour is a consequence of the interaction between the reflecting properties of materials and the nature of incidental light. But colour can also be explained from a perception standpoint, connected to psychological factors such as culture, age or education, and to physiological factors as well. The last ones are influenced by the human visual system which shows a different degree of sensitivity based on light wavelength. According to the photopic $V(\lambda)$ and scotopic $V'(\lambda)$ human response curve [3], the peak visual response corresponds to 555 and 505 nm, respectively. In photopic vision, it corresponds to a greenish yellow.

Our environment is made up of coloured surfaces and objects with different luminance which are perceived as different degrees of brightness. The perceptual response is based on a different sensitivity for different light colour. Many studies have been made in

* Corresponding author. Tel.: +34 93 4010868.
E-mail address: juditlb@yahoo.es (J. López-Besora).
[1] Tel.: +34 93 4010868.

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the field of brightness and colour, some of them referring to lamp properties and perceived brightness with a variety of experimental techniques [4]. When referring to illuminated surfaces most of them compare samples of colour in terms of brightness and in contrast with a lighter or darker background and by means of double-booth experiments [see Ref. [5] and references therein]. Other experiments have been reported with fixed, reduced scenes (covering less than 0.1 sr solid angle from the point of view) with scale-models of exterior spaces at relatively low levels of lighting [6]. In some cases, the results referring to comparison with different light sources were given [7]. Nevertheless, from the point of view of architectural spaces, which corresponds to a three-dimensional experience, there is little research. Some of them have analyzed the consequences of brightness and surface colour in spaces in terms of light perception at the levels found in architectural spaces as offices and homes from a theoretical standpoint [8], focused on the surrounding illuminated surfaces appearance, with the conclusion that in some cases, even at lower levels, great visual satisfaction can be achieved. Other studies [9] show that surface lightness seems to influence the perception of room height, especially when applied to walls and ceiling.

Furthermore, the perceptual response to colour in spaces has been studied by authors such as in Ref. [10] or [11], in terms of the psychological and physiological response to coloured environments. Mahnke [11] reports an experiment carried out by him with the purpose of determining the reaction of participants in front of coloured light. The results show the stimulating effect of red and orange, while blue and green produce calming feelings. Next, the author [11] explains other experiments with coloured rooms instead of coloured light. Most of them are clinic experiments, and show the psychophysical reaction and the assessment of observers in front of red, yellow, blue and green spaces. In general terms, these works conclude that yellow and red spaces are stimulating, while blue and green spaces are calming.

From the results of different studies shown above, it is clear that surface colour affects the perception of spaces in terms of dimension and lightness, and it has even an influence on the mood of the users.

Even though brightness and psycho physiological judgement are important when comparing different coloured surfaces under the light, other factors related to the individuals take part in the perception process. For example, the users' attitude in front of light, which may have no connection with the physical parameters given, as it happens with the perception of glare related to the type of window view [12] and the interaction of users with lights and blinds irrespective of lighting conditions [13,14].

On the other hand, although the integration of daylighting in buildings contributes to reduce the amount of energy destined for lighting, it may lead to an increase of heat load due to an excessive solar radiation contribution [15]. Some traditional systems like the Mediterranean blind [16] or lattice windows [17] provide an efficient distribution of light indoors without overheating the space. Also, other more sophisticated systems control glazing's transmittance depending on solar wavelength in a climate-based approach [18,19]. Therefore, if a high entrance of radiation in a space is not desired, the performance of some colours in front of light can make easier to attain a better vision at lower levels.

Just like light perception in a space is affected by factors such as colour surfaces, the use of colour offers a chance to reduce the use of energy in lighting. With a higher sensation of light under the same lighting conditions, a better vision with fewer fixtures would be possible, resulting in an energy saving obtained only by design. This is an important consequence which could especially be applied in spaces where a good vision is needed, for example, transition spaces from one lighted space to a differently lighted one. Other situations, such as when passing from natural to artificial lighting or from a corridor to a working space, might profit from this study. In these cases, the effects of dark or light adaptation could be minimized.

2. Methods

With this purpose in mind, three spaces were built in a controlled set. The set was appropriate because there was room enough to move in front of the spaces as well as because lighting conditions could be adjusted. The spaces, called A–C, were of the same dimensions, 2 m wide, 1.5 m deep and 3 m high, and no ceiling, as seen in Figs. 1–4.

The U-shaped spaces were assembled with self-supporting wood panels (Fig. 3) and each space was painted in a different colour: yellow (NCS S 1070-Y10R) for Space A, blue (NCS S 1030-B) for Space B, and grey (NCS S 1500-N) for Space C. The choice started with a bright yellow because it is often associated with a sensation of light, and at the same time its wavelength is close to the point of highest sensitivity of the eye, according to the human response curve [3].

In fact, the association of yellow with luminosity can be seen in another experiment that took part in the International Association of Color Consultants seminars in the United States and Europe [11]. A group of people was asked to associate some terms such as love, hatred, peace, and others with colours. When asked about the luminous term, the vast majority associated it with yellow, both in the United States and in Europe.

In our case, the purpose was to compare a yellow with a grey with the same reflection index and with a similar blue, in terms of brightness, when lighted by the same lamps. From the measurements of luminance and illuminance taken later on the experiment, the effective reflection index of each colour was calculated. The following equation was used based on the assumption that all the surfaces were Lambertian:

$$E \cdot r = \pi \cdot L$$

As a result, the reflection indexes for each painted surface are: 0.64 for A (yellow), 0.50 for B (blue) and 0.66 for C (grey), with the used lamps.

Theoretically, under the same lighting conditions, yellow and grey surfaces would have very nearly the same luminance value, higher than the blue one. Starting from these values, the objective was to check what was perceived by a sample of observers in this situation as well as when modifying the lighting conditions. In consequence, three lighting arrangements were performed taking into consideration the availability of material and the purpose of the work.

First of all, the same lighting fixtures were used in all spaces, a 2000 W quartz halogen light in zenithal position filtered with a 50% diffuser frame so as to provide a diffuse and even light. The colour temperature of all the lamps was 3200 K. A white board was set in the upper part of the front side of each space to diffuse light and hide the lamps from the observers (Figs. 2 and 5). The colour temperature, the lamps and the power given to the lamps remained the same during the experiment, even though the light reaching the spaces was modified in three lighting arrangements, as explained below. Thermal sources were used in order to have a smooth, continuous spectral distribution of light and avoid singularities. The used "white" light had then low content of short wave ("blue") radiation.

Next, as the aim was to compare the amount of light perceived in the spaces under different lighting conditions, two light levels were set and combined: a starting level and a modified one which was half of the previous. To these ends, the lighting fixtures (lamp height and lateral baffles of the lamp) were set in order to provide a starting

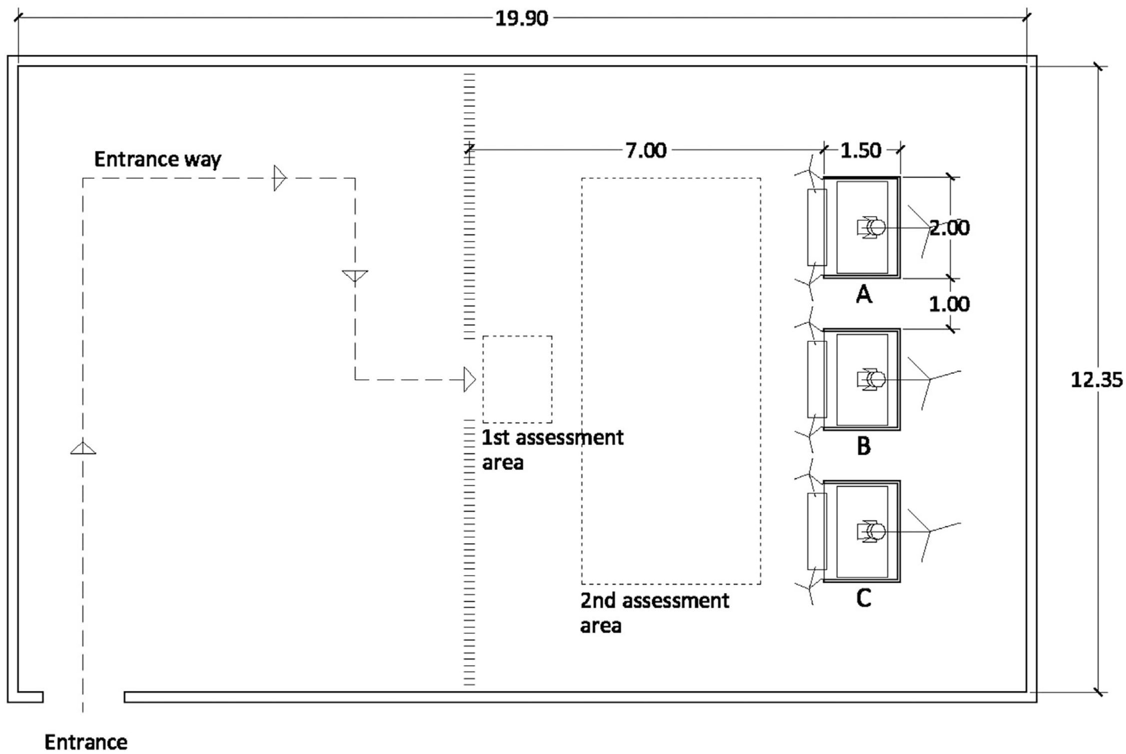

Fig. 1. Plan of the set with Spaces A–C and the assessment areas.

illuminance of approximately 900 lux at ground level. Using a filter of neutral density 3, and modifying lamp height and lateral baffles, the illuminance was reduced becoming about 450 lux.

The combination of levels led to three lighting arrangements. Arrangement 1 was set fixing the same lighting conditions in all spaces, corresponding to the higher value of illuminance. In Arrangement 2, Spaces B and C remained with the higher illuminance while Space A (yellow) was reduced to a half. In Arrangement 3 Spaces A and B remained with the higher illuminance, and in this case Space C (grey) was reduced to a half. It was dismissed to set more arrangements so as not to scatter the observers' assessment.

At the same time, the light in the spaces was assessed by a sample of volunteer observers. A total of 25 participants took part in the test, 9 males and 16 females, from 18 to 39 years old, with an average age of 25.5. The observers were organized in groups of 3–5

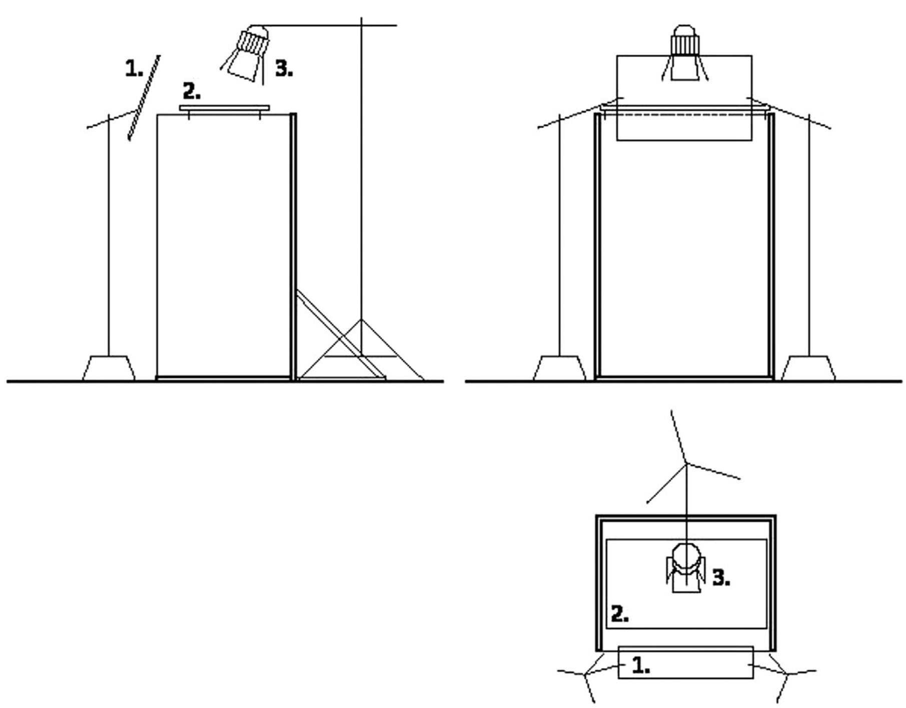

Fig. 2. Detail of the spaces and its lighting fixtures ((1) white board, (2) diffuser frame (3) quartz lighting halogen lamp).

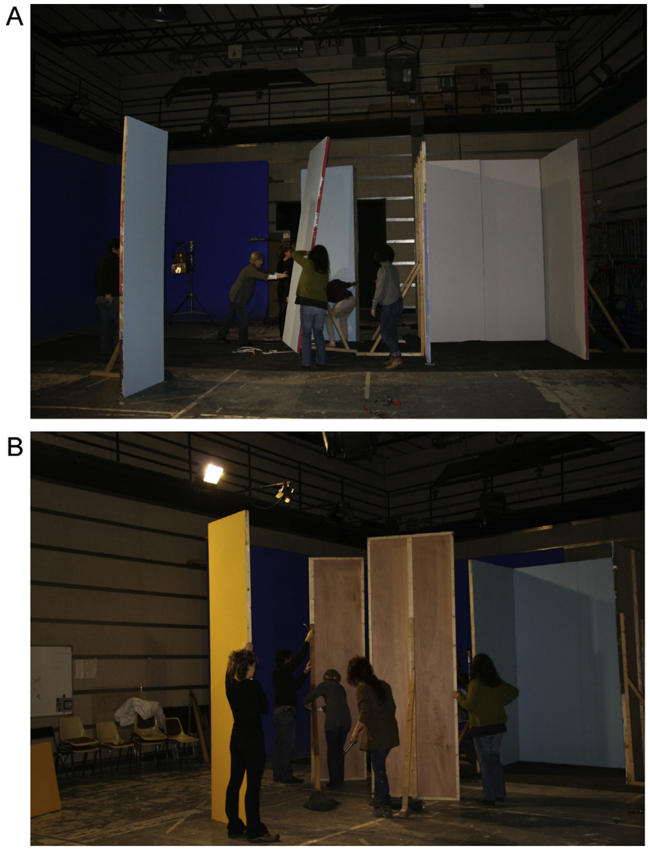

Fig. 3. Spaces assembly.

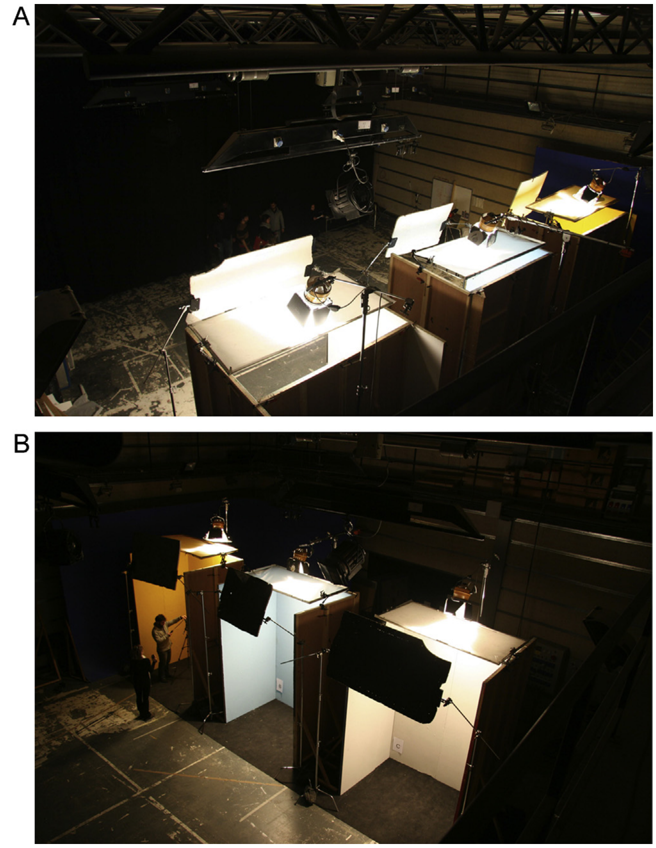

Fig. 5. Back and front view of the spaces and its lighting fixtures.

people who entered three times in the set, each time with a different lighting arrangement, and answered some questions about the perception of light and spatial brightness. On entering the set, they were immediately asked which of the spaces seemed to have more light for them, having to answer in a sheet of paper before 20 s (Fig. 6). After giving the first impression, they had a couple of minutes to move around and carry out the second assessment (Fig. 7). It consisted on answering the same question again, as well as determining which space seemed to have less light. In addition, they had to estimate the difference of light among the spaces as "almost equal", "slightly different" or "very different". The first assessment consisted only on one question in order to catch the first impression of the observers instantaneously, without time to consider other factors (Fig. 8).

Fig. 4. Front view of the set with Spaces A–C.

In what space do you think there is more light?	A	B	C

Fig. 6. First assessment questionnaire.

At the end of the process, the observers were asked some questions about the perception of colour so as to determine if any of them had any colour perception disease. As a result of the test, one of the observers showed Daltonism. The results of this subject were separated out of the group of observers.

Apart from the observer assessment, two physical measurements were taken in each arrangement. The measured parameters were illuminance and luminance. Horizontal illuminance was measured at ground level and vertical illuminance was measured in the middle of each vertical surface, 1.5 m from the ground, half width (Fig. 9). Luminance was measured in the middle of each vertical surface in order to obtain the value required to compare the arrangements and the spaces among them. In both cases, the height was decided to be 1.5 m because it is next to the average human eyes height. The relation between the luminance at the higher and the lower part of the panels was also measured, and resulted to be 9 to 1 in all cases. The instruments used in the measurements were a luminance metre Konika Minolta LS-110, and luxometres Lutron

In what space do you think there is more light?	A	B	C
In what space do you think there is less light?	A	B	C
The lightest space, in relation to the darkest one is:	Almost equal		□
	Slightly different		□
	Very different		□

Fig. 7. Second assessment questionnaire.

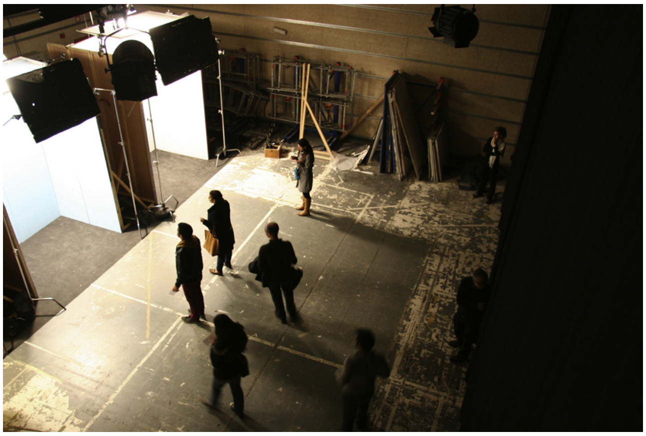

Fig. 8. Observers during the assessment.

LX-101 and HIBOK-35 (the lectures of the luxometres resulted to within 2% of each other).

3. Results and discussion

The results of the measurements were used with different purposes. The illuminance values were used to define the lighting arrangements as well as to calculate the reflection index of the colours. The luminance measurements, taken in the middle of each vertical surface, were used as physical and objective data to compare with the amount of light perceived by the observers. As the values slightly differed from lateral to frontal walls and the observers could move freely in front of the spaces, average values of luminance were considered to be the most suitable for the purpose. The value for each space results from the arithmetic mean of the surfaces that shape it, which is shown in the table below (Table 1).

The measured luminance values and the layout geometry assure that photopic condition was clearly achieved when the observers were near the spaces. According to references [20,21], scotopic range can be considered for $L < 0.01\ \mathrm{cd/m^2}$, mesopic range is for $L = 0.01$–$3\ \mathrm{cd/m^2}$, and photopic range would correspond to $L > 3\ \mathrm{cd/m^2}$.

The results of the luminance measurements show the correlation with the different light levels given to the spaces and the features of each colour. As the lamp positioning and mechanical fixing were manually made, the amount of light reaching the surfaces has a deviation margin in its values; it is for that reason that luminance and illuminance were measured in all situations and the mean values are given in the tables and graphs.

Apart from the measurements, each lighting arrangement was assessed by observers. At a first stage, the observers gave a "first impression" of the lighting condition before 20 s after seeing it (with the three spaces simultaneously). At a later stage, after being able to move and compare the spaces from different points of view and distances, a "second impression" was given. The questions and answers provided by the observers are shown in Fig. 10(a)–(c).

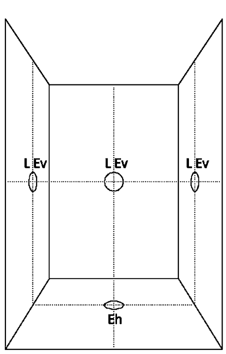

Fig. 9. Luminance (L) and illuminance (EH, EV) measurement points.

Table 1
Average wall luminance ($\mathrm{cd/m^2}$) at 1.5 m from ground level in each space.

Luminance ($\mathrm{cd/m^2}$)	Space A (yellow)	Space B (blue)	Space C (grey)
Arrangement 1	124	109	149.7
Arrangement 2	65.5	109	149.7
Arrangement 3	124	109	61.8

During the observation time, the observers were also asked to quantify the perceived difference of light among the spaces as "almost equal", "slightly different" or "very different". The answers obtained in each case are shown in Table 2.

The fact that the comparison here was performed referring to architectural spaces with some distance among them instead of small angular size contiguous fields may have affected the discrimination (for small contiguous surfaces the eye can distinguish luminances different by 2% [3]).

When comparing the luminance measurements with the observer assessment, the first thing noticed is that physics and perception do not match in all cases. In general terms, the opinion provided by the observers about the lighter and darker space is coincident with the measurements with the exception of Arrangement 1. This is so in a first assessment as well as in a more extended observation, even though in some cases the second impression tends to reduce the difference among the spaces.

In Arrangement 1, whose spaces were under the same lighting conditions, most observers thought in a first stage that Space A (yellow) offered more sensation of light than the rest, even though Space C (grey) had the highest luminance value. According to measurements, Space C was 21% lighter than Space B and 37% lighter than Space A. This is not a large difference referred to the optimal discrimination of luminances by the eye (see p. 569 in Ref. [3]) and, in fact, the observers' opinion show that none of them found the light in the spaces "very different", as it actually was. In particular, 46% of the observers found them "almost equal" and 54% "slightly different", which is close to reality. After a couple of minutes, the majority continued thinking that Space A was brighter, but to a lesser extent since some votes went to Space C. When asked about the darkest space, the opinions were given in reverse order of the other question so, Space B (blue) was assessed as the less bright in front of C and A, which corresponds to the measurements.

The fact here is that the space painted with yellow seemed brighter, especially when seen for the first time, even though the measured luminance showed that it should have been the grey one. This perception is weaker after a little time, which would suggest that the effect of this yellow is short.

In the following arrangements, one of the spaces was darkened and the other two remained with a higher level. In Arrangement 2, Space A (yellow) was set as the darkest space and the observers clearly perceived it, as well as Space C (grey) was perceived as the brightest. According to the luminance measurements, Space C (grey) was 128% lighter than A (yellow), which is a significant difference. In fact, 4% of them found that the light in the spaces

Table 2
Percentage of answers given to the question about the degree of light difference in the spaces.

	Almost equal	Slightly different	Very different
Arrangement 1	46%	54%	0%
Arrangement 2	50%	46%	4%
Arrangement 3	25%	58%	17%

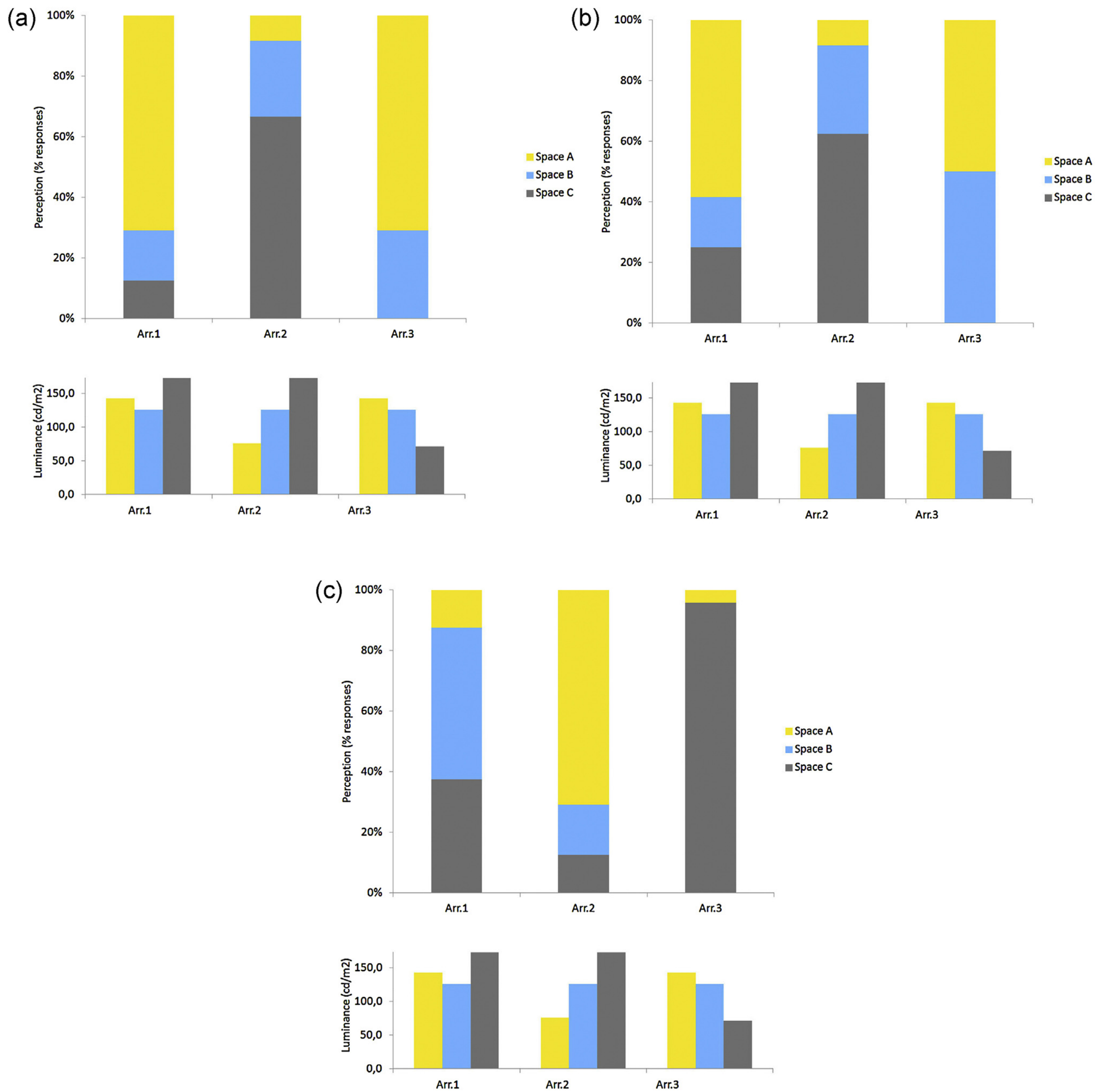

Fig. 10. (a) Percentage of responses given to the question: In which space do you think there is more light? In a first assessment. (b) Percentage of responses to the question: In which space do you think there is more light? After two minutes. (c) Percentage of responses to the question: In which space do you think there is less light? After two minutes.

was "very different", while the rest of the opinions were divided into "almost equal" and "slightly different". As in Arrangement 1, most observers did not perceive a big difference among the lighted spaces, but here it appears a small percentage, who easily noticed it. In this case, the opinion in a first stage and after a couple of minutes did not differ much. The percentage remains similar with a slight deviation from the grey space towards the blue one.

The last arrangement to be assessed (Arrangement 3) had a darker space than the others, Space C (grey). According to measurements, Spaces A and B offered a similar value, and Space A (yellow) was twice as light as Space C (grey). In a first stage, the observers clearly perceived Space A as the lightest, and none of them considered Space C as such. Space B stayed in a halfway position. When analysing the degree of difference perceived by the observers, it is noticeable that the percentage of them who found the light in the spaces "very different" rose to 17% while the percentage of "almost equal" fell to a 25%, much lower than the results of the other arrangements. The observers' opinion in this case was less ambiguous than in the preceding cases, resulting in a higher percentage of them who clearly noticed the difference. On the other hand, unlike Arrangements 1 and 2, the opinions after a couple of minutes changed considerably. After this time, the opinions about the lighter space were equally divided between Space A and Space B. The effects of yellow seem to have nearly faded after the first impression. Similarly, from the observers' opinion, Space C clearly remained as the darkest, with the vast majority of votes.

It is remarkable that, despite the luminance difference between the yellow and the grey space, in all cases there was a tendency to assess the yellow as brighter. It is clear in Arrangement 1, where the grey space had a higher value of luminance than the yellow and the opinions were the opposite. But it happens also in the other situations, where the assessment matched with the measurements in general terms, but the tendency to assess the yellow space as brighter was the same. While in Arrangement 2 the grey space was more than twice lighter than the yellow one, there was a percentage of observers who thought that yellow was the lightest. Even when the situation was the opposite, as it happened in Arrangement 3, none of the observers gave their opinion in favour of the grey space as the lightest.

Also interesting is the change of opinion after a while, or the effects of time in the perception. The most defined difference occurred in Arrangement 3, where the votes given to yellow decreased in favour of blue until dividing the answers to half-and-half. In the other arrangements, the tendency was the same, but in a smaller proportion.

It can be extracted from the results that the use of colour in architectural surfaces affects light and spatial brightness perception. From the work presented here, the lapse of perception time, the colour used and the existing light level are determinant in the perceptual response.

One of the direct consequences of this study is connected with the use of energy for lighting. An approximation of the savings potential with the use of yellow coloured spaces could be obtained considering the values shown in Table 1 and the observers' assessment in Fig. 10. In Arrangement 1, for example, the C space (grey) had more light than the A space (yellow), but judgement of people did not recognize this fact. According to the luminance differences, $\Delta L/L = 0.17$, a rough evaluation can be made: as less light was able to achieve the same lighting effect when the space was yellow, it would mean that a 17% less energy could be used in lighting the spaces. If it were possible to apply yellow in a third of the spaces of a building, this would imply near 6% of savings in lighting.

4. Conclusions

Here, a case study in which three coloured spaces were assessed by observers under different lighting conditions was analyzed. After the measurements of luminance and observer assessment, it can be concluded that even though yellow and grey surfaces had very nearly the same reflection index, the perception of spatial brightness was not the same. For example, under the same lighting conditions, the grey space looked dull and dark while the yellow one seemed cheerful and bright. Nevertheless, the effects of yellow seem to be transitory, according to the changes of opinion after the first impression. In all cases, the number of opinions in favour of yellow space as the lightest decreased after a short period of time, especially in Arrangement 3. On the other hand, it was detected that the blue space had a better light performance than expected. Although having the lowest reflection index (and then lowest luminance), in some cases it was best considered than the grey space, in terms of light. The effects of blue may be part of psychological factors that were not the object of this study, but could be analyzed in further studies.

The results obtained in this experiment bring about a potential to improve the building performance in terms of energy use and reduction of heat load by means of better visual comfort. From the results of this work, it has been deduced that at the same light level, the yellow space seemed brighter than the grey or blue one, provided that similar reflection indexes are used. If under the same lighting conditions yellow surfaces seem brighter, a reduction of artificial lighting can be performed, which implies a lower use of energy and a reduction of heat load due to the lighting fixtures and equipment. Considering the luminance differences between those spaces and the observers' assessment, a rough evaluation gives an energy savings potential in lighting of near 6%, which also implies a reduction of green house emissions to the atmosphere.

In consequence, these results should be taken into account in architecture, especially in interior design, where the perception of light is vital for visual comfort and the appearance of space. The effects of yellow can be applied in the design of entry spaces of buildings, corridors, stairs, etc., since these spaces could take advantage of the transitory condition of its effects. Apart from this, yellow surfaces and/or yellow filters might give the impression, for a space with some natural light, that a grey, cloudy day is only partially cloudy. Despite all the benefits explained, it does not mean that some colours should be banned or considered obligatory in interior design; it means that an efficient use of colour may help to highlight some parts of space and may contribute to a better use of energy.

In conclusion, the use of colour goes beyond a choice based on a reflection index and tastes or fashions, it is a tool which can help to reach important goals in terms of energy use and visual comfort.

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